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A Virtual Reality Platform for Musical Creation

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Abstract. Virtual reality aims at interacting with a computer in a similar form to interacting with an object of the real world. This research presents a VR platform allowing the user (1) to interactively create physically-based musical instruments and sounding objects, (2) play them in real time by using multisensory interaction by ways of haptics, 3D visualisation during playing, and real time physically-based sound synthesis. So doing, our system presents the two main properties expected in VR systems: the possibility of designing any type of objects and manipulating them in a multisensory real time fashion. By presenting our environment, we discuss the scientific underlying questions: (1) concerning the real time simulation, the way to manage simultaneous audio-haptic-visual cooperation during the real time multisensory simulations and (2) the Computer Aided Design functionalities for the creation of new physically-based musical instruments and sounding objects.

Keywords: physical modelling, haptic interfaces, virtual reality, musical creation, multisensory interaction

1 Introduction

In this paper, we will focus on how Digital Musical Instruments domain can be enhanced by Virtual Reality concepts and developments. Digital Musical Instruments are one of the major research axes of Computer Music, but are rarely conceived/considered as full-fledged VR systems. On other hand, Virtual Reality environments are multi-modal by nature, but sound is rarely the main focus and is often overlooked in these systems. Consequently, very few of them are conceived for musical creation.

We present a virtual reality platform for musical creation, which qualifies for both of the above. It displays a complete virtual scene construction environment based on mass-interaction physical modelling and a real time interactive simulation environment generating visual, haptic and auditory feedback during the multisensory manipulation of the virtual scene.

1.1 Virtual Reality

One of the main pursued goals of Virtual Reality is to introduce interaction with a computer in a similar form to interaction with an object of the real world. This naturally addresses multiple senses: at least tactile / haptic, visual, and sometimes auditory. Indeed, VR systems were initially centred almost exclusively on visual environments, displaying complex scenes composed of objects that can be seen, manipulated, moved… These systems very rarely consider sound with the same level of importance as the visual or gestural aspects. Even though a few applications such as [1] put emphasis on the sound produced when interacting with a virtual object, audio is often left out entirely, or integrated as a rather secondary feature, giving audio cues for example [2]. VR environments are often based on geometric approaches including complex computational processes such as collision detection between complex shapes in large 3D scenes, and sometimes physical modelling [3]. The addition of force feedback devices and haptic interaction into virtual reality systems leads to a trade off between the usual computation rate of the 3D objects (usually 25 – 100 Hz) and the haptic interaction (classically of 1kHz or more) [4], leading to the dissociation of geometry and haptic loops through the concept of haptic rendering. Such a trade – off is critical in terms of the balance between the reachable complexity of the 3D scenes and the quality of the haptic interaction in terms of inertia, peak force or acceleration [5], haptic algorithms being then executed within a dedicated thread called the haptic loop. This trade–off becomes even more complex when introducing sound synthesis. Indeed, except cases where sounds are simply pre-recorded and triggered by an event occurring in the VR 3D scene (a collision detection for instance), introducing sound synthesis in VR systems leads to novel questions at least in terms of the organisation of the models into several sections running at different frame rates: the sound synthesis sections (44,1 kHz), require a frame rate greater than not only the 3D geometrical parts (25-100 Hz) but also the haptic parts (1 kHz at least).

Whatever the intended use, the believability of a VR scene is tied as much to the consistency between the multisensory outputs (sounds and images) as to the realism of the haptic interaction. In both cases, physical modelling gains significant importance in increasing the believability of the virtual world. This is why the VR environment proposed here is based on mass-interaction physical modelling as the common point for sound generation, haptics as well as for animated image generation.

1.2 Computer music

Since the start of Computer Music, a major research axis has been to emulate or reproduce the sounds of acoustical musical instruments with the computer, using various synthesis techniques.

The term of virtual instrument has been introduced in Computer Music, preferably to the previous term DMI (for Digital Musical Instruments) with the expansion of the real time user-control of the sound synthesis systems, as related by [6].

Many recent developments aim to integrate tactile and/or haptic feedback into DMIs [7,8,9]. It gives a stronger sense to the term virtual instrument: the user can now feel the instrument, by augmenting the auditory feedback with tactile or haptic feedback. Various works have demonstrated the relevance of haptic feedback in improving the musician's performance with a computer-based instrument [10, 11]. Hereto, mimicking the real world interaction with a virtual object lends itself particularly well to physically based modelling methods as proposed in [12].

Moreover, [13] show that the believability of a bowed string increases considerably when the haptic feedback is able to convey the acoustic vibration of the string to the musician's hand. This result has been obtained by running the haptic parts at the computation rate of the string, i.e. at the sampling acoustic rate of 44,1 kHz, and has been proved to help the musician in performing complex musical tasks, such as reversing the direction of the bow, while maintaining the vibration of the string.

However, we can note a number of strong differences between the Computer Music approach to virtual instruments and VR as described above: first of all, the Computer Music approach is rarely concerned with visual representations of the virtual object, most often using control visualisations for the audio synthesis or completely detached visualisations. Thus, we cannot speak of complete visual-auditory interaction with a virtual object. Secondly, the frame rates cooperation is different than in 3D VR systems: the haptic loop is the fastest loop in VR and, except in [13] in which the whole virtual instrument - from gestures to sound - is computed at the highest frequency (that of the sound), the sound production is the fastest process in virtual musical instruments and the haptic loop is then the lowest. Thirdly, in Computer Music, a lot of popular systems exist, allowing the final user to design his/her DMI, whereas in VR, many platforms exist for dedicated applications (simulation & training, surgery, rehabilitation, automotive, showrooms, etc.), but very few are used for music [14]. In both cases, haptics are, to our knowledge, rarely connected with an end-user designing tool for interactive construction of a virtual instrument.

1.3 A VR system for musical creation

The aim of our work is to integrate the principles of VR into the context of musical creation and virtual musical instruments: interactive design and multisensory playing associating haptics, sound and vision.

Concerning modelling, we propose a modular environment for constructing virtual instruments and scenes composed of many interacting instruments and sound objects based on physical modelling.

Concerning haptics, we implemented the high quality situation in which the haptic interaction is supported by a high performance haptic device, and is closely linked to the physical modelling of the instrument, for example by running at the same higher frame rate of the sound rate simulation. Thus, the instrumentalist will be intimately in contact with his/her instrument during playing.

Concerning vision, we believe that introducing visualisation in the designing and the playing of virtual musical instruments will considerably improve the playability, the pleasure, the efficiency, and the creativeness in the musical playing. By visualisation, we mean not only seeing the geometry of the instrument, but a new functionality consisting in rendering visible some features of the vibrating behaviour of the instruments, in order to reinforce their presence and believability.

Concerning sounds, they are produced by means of physical modelling for all the parts of the instruments: vibrating and non-vibrating sections, as well as interactions between multiple instruments.

The auditory, haptic and 3D visual feedback of the manipulated physical objects occur in real time during simulation, and all stem from the physical behaviour of a unique simulated vibrating object, which is not the case with analysis-synthesis approaches such as [1]. Therefore, our system is a full multisensory virtual reality platform for musical creation.

The following section will present our new platform, first by introducing the formalism and tools used to construct virtual physical objects, then characterising the essential features of our simulation system. We will then discuss examples and models of virtual musical instruments.

2. Our New VR Platform for Musical Creation

We now present our virtual reality platform for musical creation, based on, for the first time, the integration of three basic components: (1) the CORDIS-ANIMA physical modelling and simulation formalism [15], (2) the GENESIS interactive modeller for musical creation [16] and (3) the high fidelity ERGOS haptic technology [17]. The environment is composed of two communicating parts: a modelling section in which the user is able to design his/her own physically – based musical instrument or sounding object in an interactive way, and a second section in which he/she is able to play with his/her virtual instrument by way of real time haptic, audio and 3D visual multisensory interaction. We will now introduce each component of our system.

2.1 An interactive modeller to design physically-based musical instruments

The CORDIS ANIMA formalism. The modelling and simulation processes used in our VR Musical environment are based on the CORDIS-ANIMA formalism [15], a modular language that allows building and simulating physical objects by creating mass-interaction networks based on Newtonian physics.

Briefly, it is composed of a small number of basic physical modules that represent elementary physical behaviours. These modules can be assembled to build complex physical objects. There are two main modules types in CORDIS-ANIMA: the <MAT> (mass type modules): punctual material elements, possessing a spatial position and inertia, and the <LIA> (interaction type modules): modules that define an interaction between two <MAT> modules. Thanks to the formal modules schemes, a wide variety of <LIA> modules can be developed and inserted into the modelling system, from simple linear interactions such as springs and dampers, to more complex nonlinear ones such as dry friction as needed in modelling bow-string rosin interactions for violin or cello simulations.

A specific implementation of the CORDIS ANIMA simulation engine has been designed for our presented platform and is discussed in section 2.3.

GENESIS as a Virtual Reality modeller. GENESIS [16] is a physical modelling software for musical creation. Its modelling language is based on a subset of CORDIS-ANIMA module types. It disposes of advanced tools for creating physical structures and tuning their acoustic and mechanical properties and has matured into a complete, elaborate and user-friendly environment for musical creation by means of physical modelling. We have extended GENESIS into a VR haptic modeller for real time force-feedback interaction with simulated physical models.

GENESIS was initially designed to create physical models of vibrating physical structures for off-line simulation. Indeed, for sounding objects, the simulation as well the synthesis rate must be at the audio/acoustical scale, i.e. at 44,1 kHz, in respect to the vibrating qualities of the virtual objects, which directly produce the audio output.

GENESIS models are also computed in a 1D space, meaning that all physical elementary modules move along a single vibration axis. Acoustics of musical instruments show that, in many cases, the one-dimensional main deformation, such as for example the transversal deformation of a string or a plate, is the major contributor to the sound. This is why synthesis tools usually compute one or several scalars signals that are those finally sent to the loudspeakers. This choice allows for optimised computation, enabling the design of very large physical structures. Nevertheless, auditory phenomena linked to the spatiality of 3D models can be obtained in a 1D space by using non-linear spring interactions, as related in [18], at a fraction of the cost of full 3D computation.

However, as it is based on multi-scalar non-meshed physical models, GENESIS has been extended with visualisation processes, which aim to reconstruct a 3D real time representation of the acoustical deformations of the instruments.

GENESIS allows for the design of complex instruments and sounding objects, dynamically interacting together through physical interactions, composing complex instrumental structures as used in the physically-based orchestra shown in Figure 1, composed of tens of thousands interacting physical elements [19].

Extending GENESIS as a VR haptic modeller requires introducing the representation of haptic devices within the modelling functions. Here, we introduce a representation of the haptic device inside the model following the same formalism as a general <MAT> module. Thus, it can be connected to virtual objects in the same way as any other module, for instance with percussive buffer interactions, plucking or bowing interactions which can be designed by non-linear interaction modules, and much more.

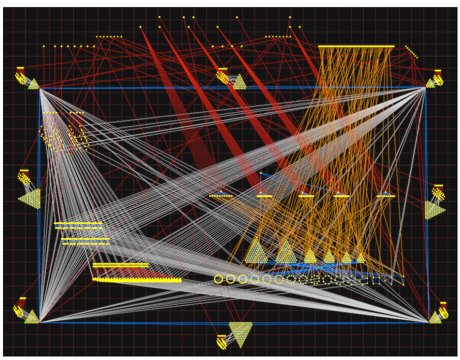

Fig.1. Representation in GENESIS of a complex physically-based orchestra by C. Cadoz, for his musical piece “pico.. TERA”

2.2 Our real-time simulation platform

We use the ERGOS high fidelity haptic technology [17] developed by ACROE and ERGOS Technologies. This device is composed of the haptic device itself, called TGR (*transducteur gestuel rétroactif*), with its electronic rack, and a dedicated "haptic board"[20], connected to a host computer. The haptic board is implemented on a TORO DSP board from Innovative Integration, which allows real time synchronous floating-point operations, with ADC and DAC converters for the haptic device position input and force feedback output. The physical simulations run in real time on the haptic board within a single-sample, synchronous, high-speed computational loop. The complete VR platform is shown in Figure 2.

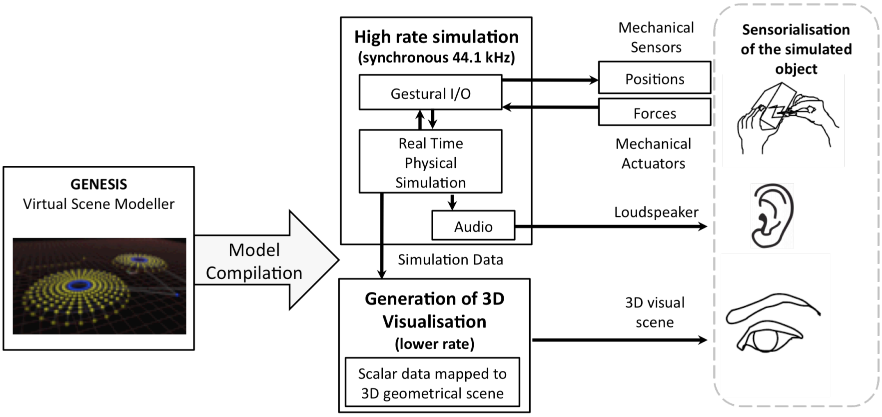

Fig.2. Our VR platform

The 12 DoF ERGOS Haptic Platform. This system has been developed in relation with the context and needs of artistic creation, specifically in the field of instrumental arts such as music and animated image synthesis. Therefore, its primary aim is to restore the interaction qualities found between the user and a traditional real musical instrument in a user/virtual instrument situation. Thus, a strong emphasis has been put on the device's dynamic performances, suited for instrumental musical gestures, as opposed to most traditional VR haptic systems centred on shape and geometrical property rendering. Mainly, the haptic device can run at very high simulation rates (ranging from 1 kHz up to 44.1 kHz) with very low latency (less than 26µs at 44.1 kHz) [13, 20], providing high fidelity in the rendering of very stiff contacts that are crucially important in percussive musical gestures and accurate frictions of bowed-string interactions.

Thanks our device's "sliced motor" modular technology, one of its main features is the potentially high number of degrees of freedom (DoF) offered by the system: from one DoF for a single slice, to a piano keyboard. In the following, each DoF will be called "a key". As opposed to most haptic systems, the ERGOS Haptic device offers several working spaces all derived from the same base design, meaning that it can be adapted for various types of manipulation of virtual objects, using morphological end-effectors ranging from separate one-dimensional keys, to 3 or 6 DoF joysticks, 3DoF bow manipulators (Figure 3), allowing a wide variety of playing styles.

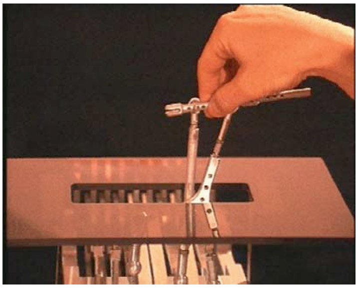

Fig.3. and 4. ERGOS Haptic device equipped with a bow end-effector (left), 12-key ERGOS haptic device equipped with piano-key end effectors (right).

From this technology, the VR environment we present disposes of a 12 DoF ERGOS Haptic system that can be configured with various combinations of end-effectors. The range of possibilities of this setup is complementary to the various interactions that can be modelled between the musician and the virtual instruments: striking, bowing, plucking, pulling, and dampening… The user is free to choose from a panoply of end-effectors, which allow him/her to adapt the morphology of the modular haptic device to the specific needs for his/her virtual instrument.

A reactive DSP simulation architecture. The TORO DSP board allows to run completely synchronous physical simulations, including sound simulation and production at rates such as 44.1 kHz and communication with haptic devices at the same rate. Below, we show the typical sequencing of a simulation step:

- Haptic device key positions are fed to the ADC converters
- A step of the physical simulation is calculated on the DSP chip.
- The calculated force feedback is sent to the DAC converters, which feed the electronic amplification system for the TGR actuators.
- The DSP board also generates the audio-output of the simulation (with single sample latency).

The acoustic output of the virtual object results directly from its physical deformations, which are picked up on one or several elements of the model and output directly on a DAC converter of the DSP haptic board. So doing, the audio output is fully synchronised with the DSP simulation running single-sample calculations and no buffering, with a latency of one single time step at 44.1kHz. There is absolutely no latency between the mechanical reaction of the virtual object and the emission of the sound created by the object's manipulation. Thus, the correlation between the mechanical interaction with the object via the haptic device and the sound it produces is complete, as in a true instrumental interaction: we mean here that the instrumentalist really takes the vibrating object in his/her hand, increasing the realism, the believability and the embodiment [21] of the virtual instrument during the playing, as demonstrated in [13].

Connection to the host environment. During the simulation, the haptic board communicates with a host system, which controls and monitors the simulation and deals with the real-time visualisation of the model, tasks that are not subject to the same latency constraints as the physical simulation haptic loop.

Relevant simulation data is streamed from the haptic board to the host system in real time: the deformations of all the masses in the model, composed of the exciters (striking devices, bows, etc.) and the vibrating structures (strings, plates, etc.) are sent. From this data, the host builds a visual scene for each frame, at a lower rate than the DSP's physical simulation, rendered according to a mapping from the multi-scalar deformation data to the geometrical space.

2.3 An optimised simulation engine

Using the TORO board for the physical simulation of acoustical vibrating objects necessarily induces a trade-off between processing power and reactivity. The TMS320C6711 DSP chip presents less processing power than many general-purpose PC processors, however it does allow completely deterministic computation at rates such as 44.1 kHz. Therefore we developed a new CORDIS-ANIMA customized DSP-optimised simulation engine that allows us to take full advantage of the chip's features.

The dual constraint for the simulation engine is its modularity, or compatibility for automatic allocation from a physical model description. This is critical for a virtual reality scene modelling and simulation system, as a non-modular simulation engine would revert to a one-shot approach, with custom simulations designed for specific models. This was the case for the previous real time simulations created at ACROE-ICA, such as [13], which were designed with ad-hoc, hand-optimised simulation programs.

A benchmarking and testing procedure has been conducted for various software architectures of DSP real time simulation engines. Throughout this procedure, we have been able to bring forward a number of important design choices for a new real time simulator.

The main performance critical criteria for the new DSP simulation engine have been found to be:

- Reducing the number of function calls (up to 70% gain by factorising the physical module functions)
- Vectorising the various data structures, including management of the DSP memory specificities (a further 70% gain).
- Using static memory allocation.
- Optimising the C++ expressions of the CORDIS-ANIMA algorithms for the DSP (excluding all division operations in the critical real time code sections, minimising conditional sections, etc.)

The new simulation engine features optimised data structures, model reorganisation for vectorised calculation of the physical algorithms and optimisation of the physical algorithm calculations according to the DSP board's architecture, while retaining a modular approach that is compatible with the generic description of physical models.

Figure 5 shows performance comparison of our new simulation environment with the previous non-modular real time engine and with the modular GENESIS off-line engine.
The results of this work have lead to a new real time simulation engine with maximal efficiency of the physical algorithms, thus, increasing the complexity of the physical models that can be simulated at audio samples rates.

Our current simulation architecture allows simulating models composed of approximately 130 to 150 modules, depending on the types of modules, number of haptic DoF… while these models are only a small subset of possible GENESIS models (which can grow to contain tens of thousands of interacting physical components), the allowed complexity is sufficient to create simple yet rich vibrating structures with up to 12 haptic interaction points (as our ERGOS Haptic device has 12 individual 1D keys). We will illustrate some typical virtual musical instruments in the examples section.

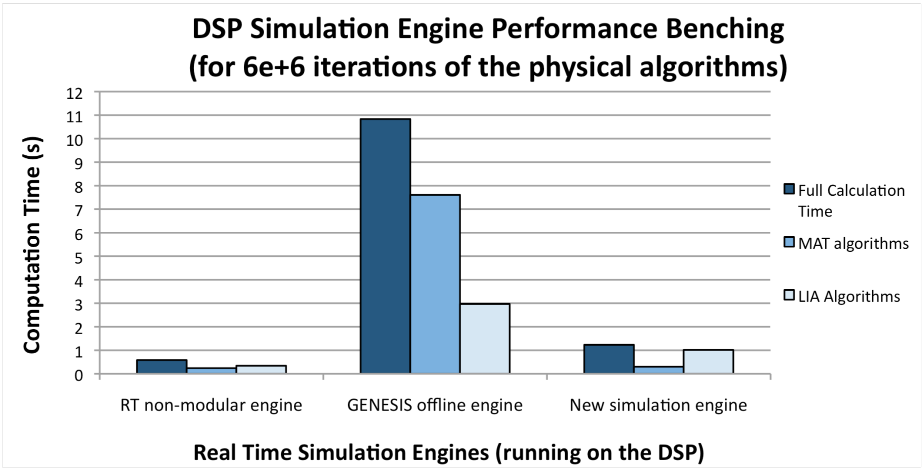

Fig.5. Performance evaluation of the new real time simulation engine

2.4 Real/Virtual interconnection

The quantitative relations between the real and virtual world are rarely studied with Virtual Reality systems. However, in our case the virtual world is designed with specific physical properties that we want to hear, see and feel in the real world. Specifically for the haptic perception of the virtual object, the user/simulation chain must be entirely characterised and calibrated, so that a given mechanical property in the simulation (for example an inertia or viscosity) is projected into the real world through the haptic device with a completely controlled and measurable equivalency between the two.
The interconnection properties between the real world and the simulation are defined by three parameters linked to the user/simulation chain:

- The real/simulation position gain,
- The simulation/real force feedback gain,
- The sampling rate of the simulated world, which in our case is 44.1 kHz.

The control of these three parameters allows complete calibration of the system with metrological precision. Furthermore, they allow the adjustment of user-defined position and impedance scales between the real world and the simulated object. For instance, it is possible to build a musical instrument in GENESIS which weighs a ton (very high impedance); the haptic properties can be adjusted to operate an impedance scale transformation so that the instrument is felt as weighing 100 g or 1 kg, while still maintaining the energetic coherency between the user's actions and the virtual object's physical reaction. Conversely, the haptic properties can be set up so that two keys, whose real displacement ranges are both approximately 20mm, are represented in the model with different scale factors: one of them could have a 1:1 position gain and the other could magnify the position by a 20:1 or even 1000:1 factor inside the model. This freedom of scales is particularly useful when designing several different interactions with a single vibrating structure, such as plucking a string with one haptic key and simultaneously fretting the string at a given length with another key. Further details concerning the user/simulation chain and our developed software tools are presented in [22].

2.5 Reconstructing a 3D visualisation of the virtual scene

As stated in the previous sections, GENESIS modelling is based on multi-scalar non-geometrical physical models. Consequently, the 3D geometry needed for the visualisation has to be reconstructed from the available multi-scalar data representing the acoustical deformations produced by the simulation. In other words, rather than having constructed a 3D vibrating object, which would have been inadequate for the relevancy of the resulting sounds and for our simulation needs, we simulate its dynamic acoustical behaviour and try to visualise this behaviour, not only from signal representations, but by visualising it in the 3D space, offering a better understanding of the vibrating properties of the object that will help the user's playing.

Designing a model in GENESIS consists in placing <MAT> modules on a blackboard and in designing their interactions. Thus, such a representation is a topological representation of the behaviour of the instrument, in which interactions represent dynamic coupling between 1D deformations supported by the 1D displacements of the masses. The geometrical mapping in GENESIS is represented in Figure 6. It consists in: (1) assigning spatial coordinates (X and Y) to the location (Bh, Bv) on the blackboard, and (2) assigning the scalar representing the deformation of the masses (which we will call a) at the Z coordinate of the geometrical 3D space.

During real time simulation, the X and Y positions in the 3D space are fixed, and the Z displacements (representing the physical deformations of the object) are communicated asynchronously from the DSP board for real time visualisation at the visualisation frame rate.

This mapping stage is part of the modelling activity in the sense that 3D representation must be coherent with the dynamics of the deformations. For instance, a string represented as in Fig.1 allows visualising the mechanical deformations associated to the wave propagation if the placement of the mass modules on the blackboard and the design of the geometrical mapping are consistent. Placing the modules randomly on the blackboard would be impossible to interpret visually, even if it generates the same behaviour.

Figure 6 shows how the data is mapped to build the visualisation, and Figure 7 shows an example with a GENESIS model. The ring structure of the object (built of mass modules meshed with visco-elastic interactions) is matched with the ring representation on the blackboard. During simulation, if the mapping is correctly designed, this spatial structure will show the waves propagating in a circular motion through the ring.

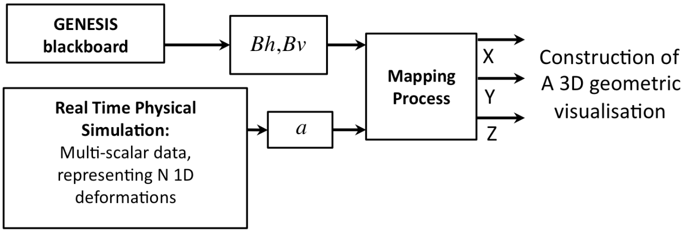

Fig.6. 3D geometrical mapping process of a GENESIS model for the real time visualisation

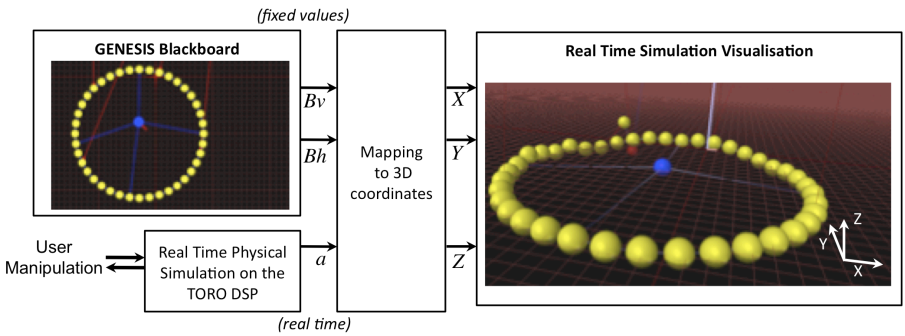

Fig.7. Example of a GENESIS model and the final animation produced during simulation.

All these components constitute our VR platform for musical creation, shown during playing in Figure 8. For the first time, GENESIS models can be played haptically in real time. Furthermore, these new developments provide our first generic modelling system for the interactive design of multisensory real time simulations based on the CORDIS ANIMA formalism. In the following section, we present a number of simple models and examples.

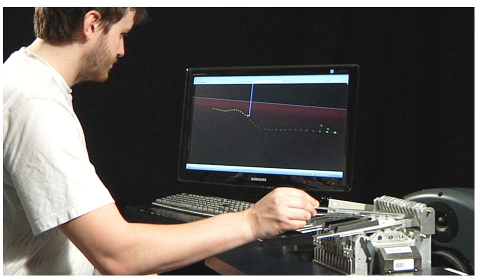

Fig 8. Manipulation of a real time GENESIS instrument; here, a bowed string model.

3. Models and Examples

The first objective of this work has been to create an extensive and user-friendly platform for designing and manipulating virtual musical instruments. In this respect, the major strength of this system is the ease with which virtual scenes can be built and experimented with. New models can be created and tested in a matter of minutes, with no need for expert knowledge neither in haptic technologies nor in real time programming. The only prerequisite is being comfortable with the GENESIS physical modelling paradigm, for which ACROE already disposes of many pedagogical tools. Below we demonstrate some of the first models created with this platform. Needless to say, this modelling and creation phase is still under way, and many more virtual instruments and scenes are in the works.

3.1 A piano-inspired model

This model, shown in Figure 9, aims to explore the full potential of our 12-key haptic device. It is constituted of 12 separate piano keys. These keys are linked to small hammer masses, which strike individual vibrating structures, tuned to various pitches. A physical "bridge" gathers all the vibrations from the vibrating structures and is used as the sound output source.

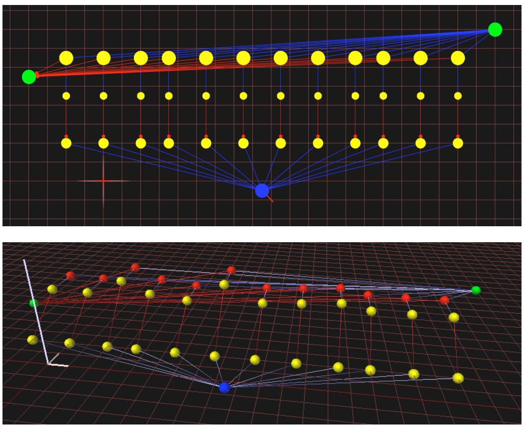

Fig.9. The Piano model: the GENESIS model on the blackboard (above) and the 3D animation during real time interaction, with the TGR keys coloured in red (below)

The physical model also contains the mechanical components of the piano-key feel: the buffer when the key is fully pressed down as well as configurable friction and inertia of the keys. The touch can be adjusted by the user to be soft or, on the contrary, very rigid. We tuned the vibrating structures of our model to play the 12 tempered notes of the chromatic scale. This basic model can be extended to incorporate more subtle components of the key mechanism and also more complex vibrating structures. Further work on the simulation hardware architecture is currently underway to allow implementing these complex models for all 12 keys.

3.3 A ring structure

This model, shown in Figure 7, generates inharmonic bell-like sounds. It is composed of a main ring structure divided into four heterogeneous sections, modelling a structure with uneven matter distribution. Each section is delimited by visco-elastic relations, which connect them to a heavy bridge oscillator. Four striking devices hit the different sections of this ring. Depending on the stiffness of the “section delimiters”, we can control the ratio between the propagation of the vibrations in the full ring and the local propagation limited to the excited sub-section.

The instrument shows different sound responses depending on where, and how heavily it is hit. Furthermore, some striking devices can be used to block certain sub-sections of the ring, stopping certain vibrations and modifying the response of the structure.

3.4 The paddleball

This model is very simple: a sheet or membrane made of MAS (mass) and REF (visco-elastic interaction) elements is connected to a TGR key though each of its extremities, the key acting as a “floating” fixed point for the membrane. Vibrations from the membrane are sent to the audio output. The other component of the model is a single MAS module, which we will call the ball. It is given gravity by applying a constant downward force value with a non-linear interaction module, and is connected to the membrane with a buffer-spring interaction. In its initial state, the ball rests against the membrane and nothing specific happens.

When manipulating the TGR key, hence the height of the whole membrane, the user can launch the ball up in the air. The ball then falls back down and bounces (with dampening) on the membrane until it rests completely against it. However, with well-timed impulses to the membrane section the ball can be sent back into the air, and the bounces can be sustained, for as long as the user can keep his gestures synchronised with the ball’s motion. In short, this model reproduces a 1D paddleball, as shown in Figure 10.

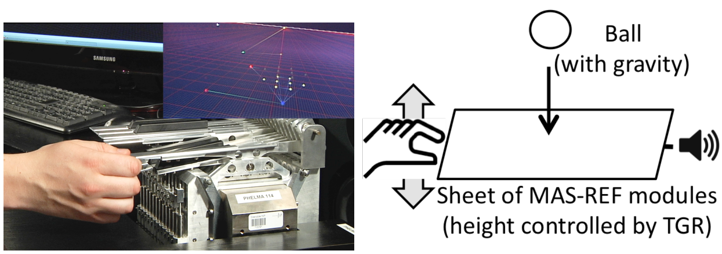

Fig.10. The paddleball model

The impacts of the ball on the membrane are felt, heard and seen by the user. Succeeding in maintaining the ball’s bounces is not a trivial task, and proves very difficult when removing information relative to certain sensory channels (muting the audio, removing the force feedback, or removing the visualisation). This goes to show the importance of physically coherent sensory feedback from a virtual object for the instrumental manipulation, as demonstrated by previous results [13]. Our VR platform is a promising tool for further exploring this research by conducting user experiments in various virtual situations.

4. Results and Observations

Real time multisensory manipulation of the virtual objects depicted above proves highly satisfying, offering subtle and intimate control over the sound production by respecting the energetic coherence between the user and the virtual object. Four points can be mentioned:

First, the properties of the TGR and the architecture of the simulation make for a high quality restitution of the mechanical properties of the virtual objects. Hard contacts can be rendered and the mechanical feel of an instrument can be entirely modelled. This makes the system very versatile, as we can truly craft the virtual instruments for the desired feel and playability. Our "piano" model, although it does not entirely model the mechanical complexity of the real instrument, proposes a complete and playable musical interface.

Secondly, the intimate coupling between the musician and the virtual instrument allows for a very fine control of the generated acoustic phenomena. Our first qualitative observations, gathered with a group of 20 participants (musicians and non-musicians) have showed that even with our first and fairly simple models, the users actively explore the possibilities in terms of gestures and sounds, of causes and consequences. Very quickly, they take the instruments in hand and learn how to produce a wide variety of (sometimes surprising) sounds. In the same way as [21], it seems that the virtual instruments present a positive assimilation curve, acquisition of knowledge and skill increase through the interaction. This leads us to say that the musician/instrument relation is similar to that of a traditional musical instrument, in the sense that the instrument is freely and intuitively manipulated and embodied by the user, in the gesture-sound relation.

Furthermore, the 3D visualisation of the physical object's deformation during manipulation is an asset of our system that is not present in the natural instrumental situation. More than just seeing the instrument during playing, our system offers an extensive visual representation of the simulated physical object, allowing for instance to magnify the visualisation of it's physical deformations. Not only can the user manipulate a complete multisensory simulated instrument, but he/she can also simultaneously benefit from a detailed visualisation of the vibratory behaviour of the instrument during playing (imagine playing a violin and being able to simultaneously visualise all the vibratory deformations of the strings and body!). From our qualitative studies, we can say that this visual representation, allowed by our VR approach, adds to the experience of playing the instruments, and to the understanding of the instrument's behaviour during playing.

Finally, as pointed out by the paddleball model, the scope of this platform is larger than virtual musical instruments alone. Any number of virtual scenes and scenarios can be imagined and created, presenting the user with a full, physical and energetically coherent audio-visual-haptic experience.

5. Conclusions

This paper presents a new virtual reality platform for musical creation, composed of the GENESIS physical modelling environment, a high performance TGR haptic device, and a real time simulation environment for haptic interaction with virtual scenes.

From a musical perspective, the quality of the haptic device and the full physical modelling of the virtual objects enable full dynamic coupling between the musician and his instrument, resulting in expressive playing. From a larger perspective, this platform is a complete audio, visual and haptic virtual reality station, presenting an advanced scene modeller and a complete simulation environment, offering a unique tool for further exploring the influence of the coherence of visual, haptic and audio feedback for designing perceptually convincing virtual objects.

We aim to extend this platform with several new features. First, a new simulation hardware architecture is in progress, which significantly increases available computing power. Secondly, we aim to introduce multirate physical models, in which complex mechanical sections will be calculated at a lower rate while vibrating structure sections will be simulated at audio rates, both sections remaining physically coupled and energetically coherent. Finally, we aim to integrate the various TGR end-effectors into our system, specifically complex spatial morphologies such as 3 DOF and 6 DOF systems, and allow for multiple haptic simulation platforms to connect to a same virtual scene, enabling many DOF multi-user manipulation experiments.

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